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ION-SENSING USING CHEMICALLY-MODIFIED ISFETs

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Abstract

Synthetic macrocyclic polyether ion receptors are the active components for the selective and sensitive detection of potassium ions in chemical sensors based on modified ISFETs.

Covalent chemical anchoring of the sensing membrane to the gate oxide of the ISFET is essential in order to increase the lifetime of the sensor system to more than three months.

Introduction

This contribution describes the use of synthetic receptor molecules in the development of chemical sensors. Since the discovery of macrocyclic polyethers ('crown-ethers') by Pedersen [1], much research has been carried out [2] on the design, synthesis and selective complexation of cations and polar organic molecules by crown-ethers. If the complexation reaction occurs in a polymeric membrane, which is in contact with an aqueous electrolyte solution, a so-called membrane potential can be developed. Using an ion-sensitive field-effect transistor (ISFET) as the transducer of the created membrane potential, it is possible to design a chemical sensor system for the detection of cations and polar organic molecules. The selectivity and sensitivity of the chemical sensor are predominantly determined by the chemical structure of the receptor molecule. By a proper choice of receptor molecule, in principle anions can also be sensed by such a system.

Chemical recognition

The term chemical recognition is used to describe the selective complexation reaction of a substrate and a synthetic or biological receptor molecule (Fig. 1). The driving force for these *reversible processes* may be ion–dipole, dipole–dipole, and/or hydrogen bond interactions. Some illustrations

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TABLE 1

Some examples of chemical recognition by crown-ethers

Interaction type	Example	Ref.
Ion–dipole	dibenzo 30-crown-10 + potassium log K = 4.57 (MeOH, 25 °C)	3
Dipole–dipole	18-crown-6 + nitromethane log K = 0.48[a] (benzene, 9 °C)	4
	18-crown-6 + malononitrile log K = 2.83 (benzene, 9 °C)	4
Ion–dipole plus hydrogen-bonding	benzo 30-crown-10 + guanidinium log K = 1.83[a] (MeOH, 25 °C)	3

[a] 1:1 adduct.

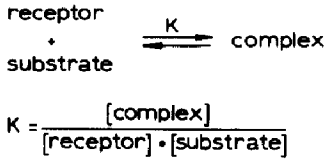

Fig. 1. Chemical recognition.

are shown in Table 1. The association constant K (Fig. 1) determines in a given medium the sensitivity of the receptor molecule, and therefore the lower detection limit of the sensor, while the size and shape of the receptor molecule determine to a great extent the selectivity for complexation. This principle can be used in facilitated membrane separation [5], in catalysis and in chemical sensors.

Potentiometric chemical sensors

In a potentiometric chemical sensor the synthetic receptor molecule is immobilized in a polymeric membrane. One side of the membrane is in contact with the analyte solution to be probed. By reversible exchange of the ions between the analyte solution and the membrane phase, accompanied by the complexation process in the membrane phase, a membrane potential will be developed. This potential difference (ΔE_m) is tranduced into an electronic signal by an ISFET, positioned on the other side of the membrane (Fig. 2).

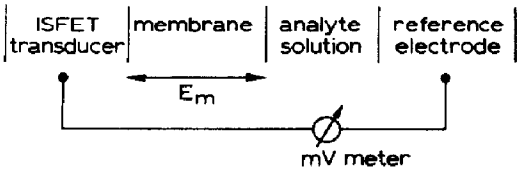

Fig. 2. Simplified schematic representation of an ion-selective chemical sensor system.

In the ideal case a Nernstian response is observed by varying the ion activity a_i in the analyte solution. For univalent ions the following equation is applicable:

$$E_m = E_0 + \frac{2.303\,RT}{F} \log\{a_i + \Sigma K_{ij}^{Pot} a_j\} \quad (1)$$

where E_m = membrane potential
E_0 = standard membrane potential
R = gas constant
T = absolute temperature
F = Faraday constant
a_i = potential determining ion
a_j = interfering ion
K_{ij}^{Pot} = potentiometric selectivity constant.

It is evident that all other liquid and solid junctions in the depicted system have to be maintained constant and thermodynamically defined [6].

The ISFET as potential transducer

The most important reason to use an ISFET as the transducing element, instead of a (coated) metal wire for instance, is that the ISFET transforms the high-impedance input signal (E_m) directly into a low-impedance output signal. This eliminates almost completely the effect of disturbing external electromagnetic fields and it is therefore not necessary to use shielded connecting wires. Other beneficial aspects are the robustness of the sensor and its small dimensions. If the polymeric sensing membrane can be fixed by integrated circuit (IC)-compatible technologies, *i.e.*, photolithography, it is also possible to manufacture cheap multi-ion sensors.

The modified ISFETs have been operated at a constant drain–source potential of 0.5 V and constant drain-current mode of 100 μA by offsetting the analyte–membrane potential jump by an equal and opposite potential via the reference calomel electrode. In our experimental set-up (Fig. 3) ten (modified) ISFETs are monitored simultaneously and the data are collected and handled using an Apple II microcomputer.

Membrane-modified ISFETs

A simple [7] and routine method used by us for investigation of the sensing properties of newly synthesized macrocyclic receptor molecules is the incorporation of these molecules in a plasticized PVC matrix, which is *physically* adsorbed on the silicon dioxide gate of our ISFETs. In this way the potentiometric selectivity constants can be determined using the mixed-solution method [8] for the different macrocyclic polyethers.

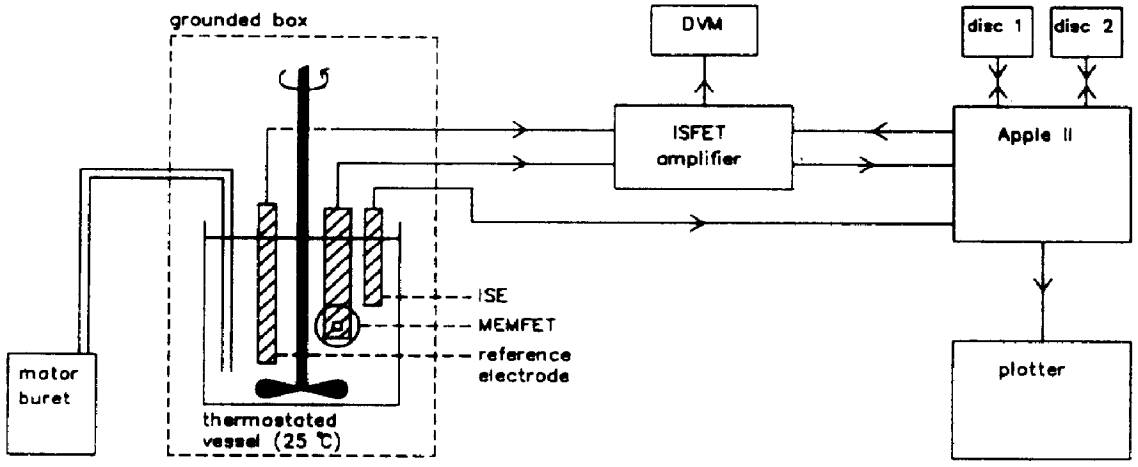

Fig. 3. Schematics of (modified) ISFET measurements.

However, the use of plasticized PVC membranes to modify ISFETs has some important shortcomings: (i) since the membrane is physically bound to the chip, it has a short lifetime as a consequence of the interpenetration of water molecules; (ii) the plasticizer can leach from the membrane, making the plastic brittle; and (iii) the ionophore can also leach from the membrane, resulting in an aselective membrane.

At the University of Twente the following strategy has been developed to solve these problems: (i) the membrane is bound covalently to the chip, leading to an increased adhesion; (ii) intrinsic plastic polymers ('elastomers') are used, eliminating the external plasticizer; and (iii) the ionophore will be covalently linked to the polymer backbone. Research on this topic is in progress in our laboratory. In the next Section the aspects of covalent bonding of polymeric membranes to the ISFETs will be discussed.

Covalent anchoring of membranes

A key step in the development of long-lifetime membrane-modified ISFETs is the silylation of the SiO_2 gate oxide with organofunctional silanes [9]. The silane reagent couples to the SiO_2 interface by the formation of siloxane bonds [10] (≡Si—O—Si≡; Fig. 4). In this way the surface is covered by organo-functional groups, making subsequent covalent bonding of a

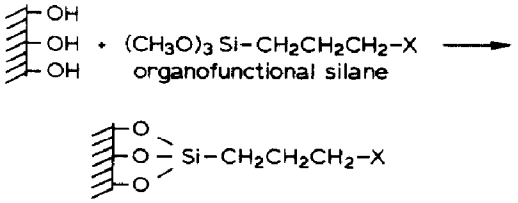

Fig. 4. Silylation of the SiO_2 gate oxide.

polymer possible. For instance, a methacryloxypropyl-trimethoxysilane modified ISFET can be coated with a prepolymer of butadiene, followed by photopolymerization. During the polymerization process the prepolymer grows and also binds to the methacryl-modified surface (Fig. 5). Durability tests were performed on these modified ISFETs to demonstrate the effect of covalent bonding (Fig. 6). It is clearly seen that even after three months in contact with an aqueous solution, the covalently-bound membrane is still present on the ISFET, whereas for physically-bound membranes the lifetime is only a few days.

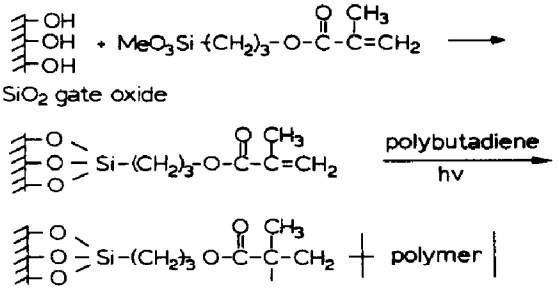

Fig. 5. Covalent binding of butadiene membranes.

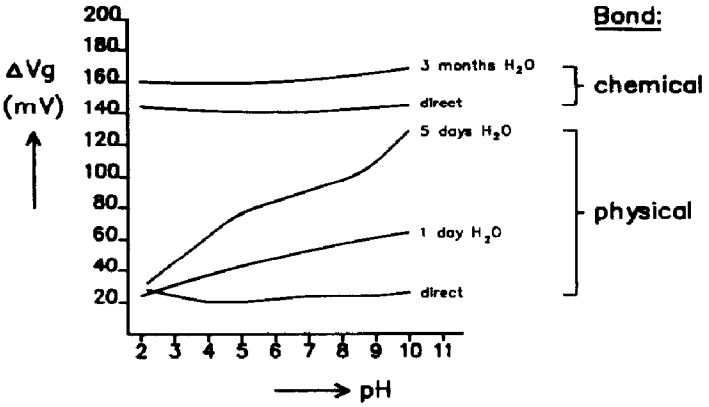

Fig. 6. Effect of immersion time on the pH-response of physically- and covalently-modified ISFETs.

Conclusions

We have demonstrated that polymeric membranes can be covalently bound to presilylated ISFETs, leading to a long-lifetime chemical sensor. For preference, photopolymerizable monomers or prepolymers are used in order to perform IC-compatible photolithographic procedures. The formed polymeric membranes must have elastomeric properties. Synthetic receptor molecules are useful in the design and development of chemical sensors, because they can be linked to the polymeric backbone.

Acknowledgement

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